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MECHANICAL RELIABILITY AND PLANT PERFORMANCE

by

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A two state statistical model is proposed for studying the effect of equipment outages on plant performance. Simulation of lost treatment capacity in an activated sludge treatment system indicates the degree to which BOD violation frequencies are much more sensitive to lost aeration capacity than to lost clarifier or return sludge pumping capacity. A framework for utilizing the model to select cost-effective levels of design redundancy is presented. A simplified version of the procedure is applied to the design of an aeration system.

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Mechanical Reliability and Plant Performance

Lewis A. Rossman*

A two state statistical model is proposed for studying the effect of equipment outages on plant performance. Simulation of lost treatment capacity in an activated sludge treatment system indicates the degree to which BOD violation frequencies are much more sensitive to lost aeration capacity than to lost clarifier or return sludge pumping capacity. A framework for utilizing the model to select cost-effective levels of design redundancy is presented. A simplified version of the procedure is applied to the design of an aeration system.

Introduction

Increased attention is being given to the capability of wastewater treatment plants to meet their NPDES discharge permit requirements (7,17). One factor that can cause substandard treatment performance is excessive mechanical breakdowns (14). This study attempts to estimate the impact that mechanical equipment failure frequency has on the effluent quality of an otherwise well designed and operated treatment plant. Procedures are developed for determining which treatment subsystems are critical in terms of mechanical reliability and for determining cost-effective design choices of component redundancy and excess capacity.

A conceptual model for studying the effect of equipment outages on plant performance is proposed. It assumes that a plant operates in one of two states: a normal state in which all treatment units are on line, and a reduced capacity state in which a treatment unit in some sub-system (e.g., a clarifier or blower) is unavailable due to mechanical problems or preventive maintenance. In both states effluent quality displays a daily variation due to process related "noise" but with the mean value higher in the reduced capacity state than in the normal state. Hence, effluent limit violations while in the reduced capacity state should be more frequent. The magnitude of this increase will depend on the size of the unit and its probability of being off line.

Criticality Analysis

A conventional activated sludge system is first studied to determine where reduced treatment capacity due to equipment outages is most critical in causing effluent violations. A steady state mathematical model is used to relate reductions in clarifier, return sludge pumping, and aeration capacity to resulting mean effluent BOD concentration. It includes the following features:

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* suspended solids removal in primary clarification is a function of influent solids concentration and clarifier surface area (15)
* substrate utilization rates in the aeration basin follow Grau kinetics and are thus functions of influent BOD (1,6)
* three species of mixed liquor suspended solids (active biomass, refractory organics, and inerts) are accounted for (1,5)
* final clarifier performance is determined by both a clarification function and a thickening function, where sludge settling velocity and sludge volume index are related to sludge age (solids retention time) (3,12,16).

Daily variability is then introduced by assuming, as has been found for many activated sludge plants, that effluent BOD levels follow a lognormal probability distribution (2,8,10). Then the violation frequency V of an effluent limit C_L can be estimated as

$$V = 1 - F\{\log(C_L\sqrt{1+\nu^2}/C_e)/\sqrt{\log(1+\nu^2}\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where C_e = mean effluent BOD, ν = coefficient of variation (standard deviation divided by the mean) of effluent BOD, and F = cumulative normal probability function.

Simulations are carried out for a plant whose raw wastewater characteristics, treatability parameters, and design sizing are listed in Table 1. The resulting mean effluent BOD concentration with all treatment units on line is 12 mg/L. For purposes of analysis a standard deviation of 10 mg/L is assumed. This is equal to the value suggested by Niku, et al. (11) for distinguishing a "stable" effluent from an "unstable" one. The resulting coefficient of variation, 0.83, falls in the range of 0.3 to 1.3 observed in a recent survey of activated sludge plants (10). Finally, an effluent BOD limit of 30 mg/L is chosen to provide a common basis of comparison. With these assumptions, Eq. 1 gives a 5 percent violation frequency with all units functioning.

Figure 1 shows the resulting violation frequencies of the 30 mg/L limit as progressively larger fractions of treatment capacity are removed from service in each of four sub-systems (e.g., removing one out of four final clarifiers results in a 25 percent loss of surface area or an equivalent increase in overflow rate from 800 to 1000 gpd/sq ft). Assuming comparable probabilities of component availability, it is evident that system performance is relatively resilient to losses of clarifier and return sludge pumping capacity but is highly sensitive to lost aeration capacity. From a qualitative standpoint such results are not suprising and probably agree with the experience of most plant operators. The real value of this exercise is to quantify the effect that mechanical component outages may have on treatment system performance reliability. This information will next be used to explore cost-effective choices of component redundancy and excess capacity.

Redundant Design

The adverse effects of mechanical equipment failures can be mitigated by designing systems with replicate units and oversizing these units. The choice of number and sizing reflects a trade-off between cost and reliability of meeting effluent quality goals. Of course

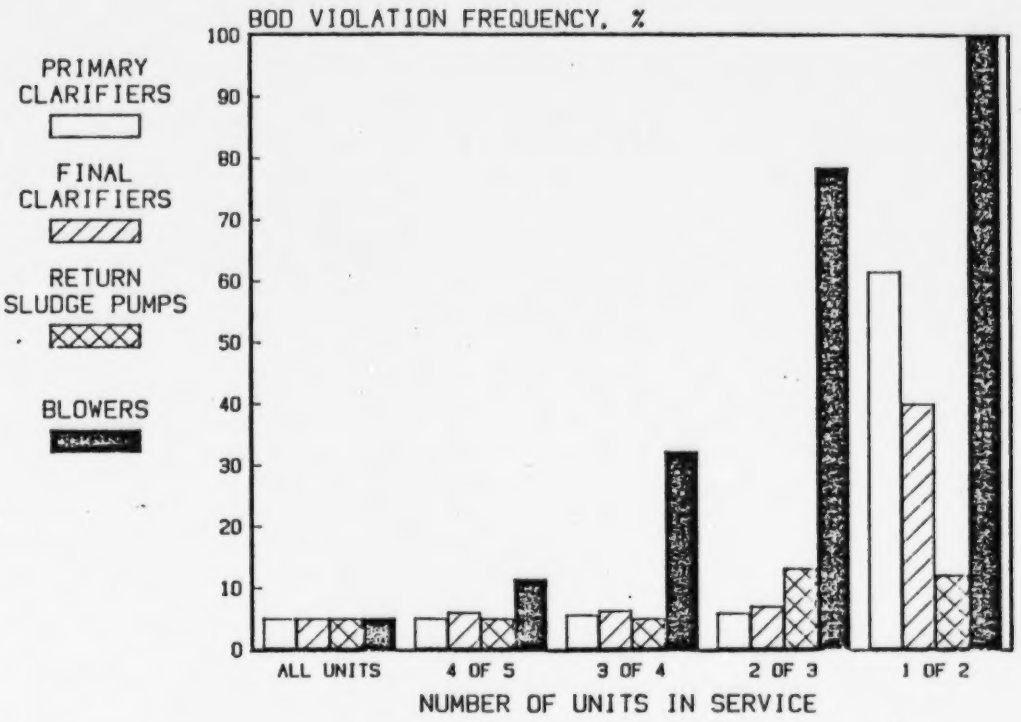

Figure 1. - BOD Violation Frequency as Treatment Capacity is Lost

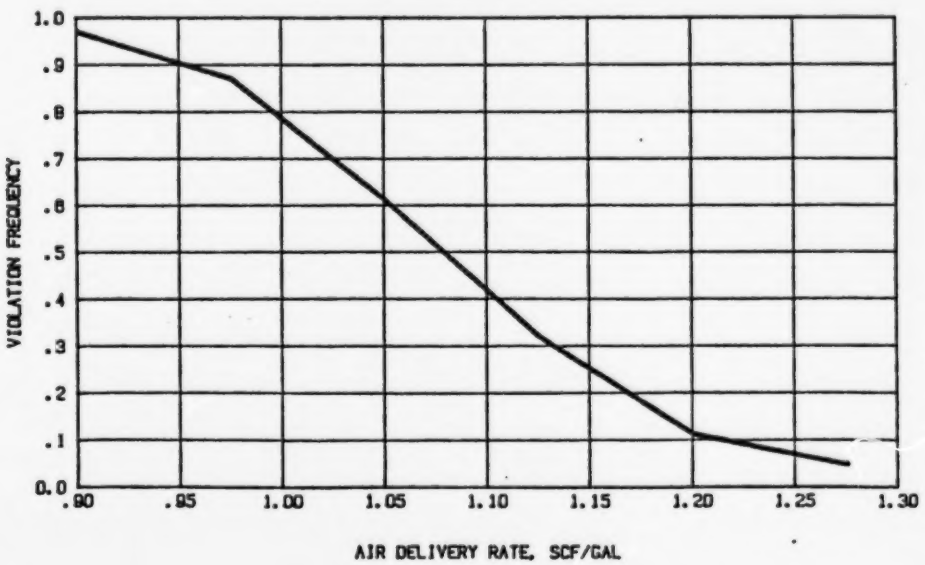

Figure 2. BOD Violation Frequency versus Air Delivery Rate

TABLE 1. - Raw Wastewater Characteristics, Treatability Parameters, and Nominal Design Sizing of an Activated Sludge System

Item (1)	Value (2)
Raw BOD, mg/L	200
Raw Suspended BOD, percent	70
Raw Suspended Solids, mg/L	250
Raw Volatile Suspended Solids, percent	75
Peak/Average Raw BOD Load	1.8
Yield Coefficient, lb biomass/lb BOD	0.5
Substrate Utilization Rate Coefficient, 1/day	10
Biomass Decay Rate Coefficient, 1/day	0.1
Mixed Liquor Settleability Parameter (12)	46
Mixed Liquor Thickening Parameter (16)	0.0006
Oxygen Transfer Efficiency, percent	5.75
Primary Clarifier Overflow Rate, gpd/sq ft	1000
Aeration Hydraulic Residence Time, hr	6
Air Delivery Rate, scf/gal	1.5
Final Clarifier Overflow Rate, gpd/sq ft	800
Return Sludge Flow Ratio	0.25
Waste Sludge Flow Ratio	0.0075

there may be other considerations that constrain the designer such as regulatory requirements, availability of equipment sizes, and construction practices.

The design redundancy question asks how many replicate parallel units (n_i) should be used in sub-system i and what should be their total sizing (x_i) so that a desired effluent limit exceedance frequency (E) is met at least total cost. If A_i is the inherent availability of a unit in sub-system i (i.e., the fraction of the time that the unit is operational) and if the losses of treatment units occur independent of one another, then for a system of S sub-systems

$$E = \sum_{m_1=0}^{n_1} \cdots \sum_{m_S=0}^{n_S} \left(\prod_{i=1}^{S} \binom{n_i}{m_i} (1-A_i)^{m_i} (A_i)^{n_i-m_i} \right) \cdot V\{(n_1-m_1)x_1/n_1 \ \ldots \ (n_S-m_S)x_S/n_S\} \quad \ldots (2)$$

The function V can be interpreted as in Eq. 1 where the mean effluent concentration is computed on the basis of each sub-system i having capacity $(n_i-m_i)x_i/n_i$. Eqs. 1 and 2, along with a set of cost-capacity functions can be used to numerically optimize the choices of n_i and x_i for a desired C_L and E (e.g., see Ref. (9) for an applicable numerical procedure).

Aeration System Sizing

Earlier it was shown that activated sludge effluent limit exceedances are most sensitive to losses in air delivery capacity. A simplified version of Eq. 2 can be used to cost-effectively size air blowers to meet a BOD limit at a given level of reliability. It assumes that (a) some nominal system design has been selected to start with that produces a desired level of BOD removal in the absence of any equipment outages, (b) the probability of having two or more blowers out of service at the same time is small, (c) blower capital costs are proportional to $n(x/n)^b$ where b is an economy of scale factor, and (d) blower operating costs can be ignored since they depend mainly on the quantity of waste treated rather than the level of design redundancy provided.

The first step is to use the nominal system design and generate a curve of BOD violation frequency V versus total blower capacity x as x is reduced from its nominal value x^o. This may be done by the formal modeling approach used to generate Figure 1 or by any other convenient and reliable method (e.g., expert judgement). Then as the number of blowers, n, is varied from 2 on upwards, the following steps are carried out:

1. Let $V_{n-1} = \dfrac{E - A^n V(x^o)}{n A^{n-1} (1-A)}$ where E is the desired effluent limit exceedance level and A is the availability of a blower.
2. Establish the blower capacity, $x(V_{n-1})$, corresponding to violation frequency V_{n-1}.
3. Set $x = x(V_{n-1})n/(n-1)$ and $C_n = n(x/n)^b$.

The n and corresponding x with the smallest C_n yields the most cost-effective number and sizing of blowers.

This procedure can be used to meet effluent exceedance frequencies ranging from 1-A down to $V(x^o)$. In the latter case it can be shown that the optimal redundancy level is to use the next highest integer from 1/(1-b) number of blowers with total capacity $nx^o/(n-1)$, i.e., enough capacity to equal the nominal sizing with one unit out of service.

Numerical Example

The above procedure is used to size an aeration system for the activated sludge system studied earlier. The nominal design of this system, as given in Table 1, can meet a 30 mg/L BOD limit 95 percent of the time during which no loss of aeration capacity is experienced. Figure 2 illustrates how the violation frequency V would increase as air delivery capacity is reduced due to blower outages. It also shows that the original nominal design value of 1.5 scf/gal can be reduced down to 1.275 scf/gal since this is the maximum amount of air needed to fulfill bio-oxidation requirements. (Note: Excess aeration capacity to handle peak diurnal organic loadings is already included in this figure.) A reasonable economy of scale factor to use for blowers is 0.7 (4). Blower availability statistics are not readily found. In one recent survey of several treatment plants an average value of 99.3 percent was reported (13). Studies of four blowers at a California plant showed their availabilities to range from 72.8 to 99.7 percent(18).

For illustrative purposes, this example will use values of 84 and 92 percent.

Figure 3 shows the results obtained by applying the sizing procedure over a range of target exceedance frequencies at the two availability levels. In this figure sizing is expressed as an excess capacity factor relative to the nominal capacity of 1.275 scf/gal. E.g., a value of 1.5 implies a total blower capacity of 1.5*1.275 scf/gal. Note that for all situations the optimal number of blowers selected is three. Figure 4 displays the relative cost ratio of these designs against their corresponding BOD exceedance frequencies. Relative costs are computed with respect to the cost of a single blower system providing 1.275 scf/gal.

These results show that both blower sizing and costs are fairly insensitive to the availability level used. A halving of the frequency of individual blower downtime hardly affects the capital cost of achieving 90 to 95 percent reliability in meeting the 30 mg/L BOD limit. Figure 4 illustrates how the procedure can generate useful information on cost-reliability trade-offs. For example, a proposal to double the allowable exceedance target from 5 to 10 percent would provide only a 5 percent savings in aeration cost.

Conclusions

A quantitative assessment of the relative impacts of mechanical component failures on activated sludge effluent quality violation frequency shows loss of aeration capacity to be more critical than lost clarifier or return sludge pumping capacity. It is possible to extend this type of analysis to make cost-effective choices of number and sizing of treatment components to meet proposed reliability levels on effluent quality. A simplified version of this methodology can be used to size aeration systems when the remainder of the plant design is first specified. A numerical example shows the optimal number of blowers to be three and that little cost savings are possible by either increasing the blower mechanical reliability or by relaxing the allowable BOD violation frequency.

The approaches used here are approximate ones. They were chosen partly for their ability to provide a simple and convenient framework for analyzing the significance of mechanical reliability on treatment plant performance. It is important to recognize and appreciate the various assumptions and simplifications on which they are based. Additional sensitivity analysis and empirical testing are needed to provide more confidence in their applicability.

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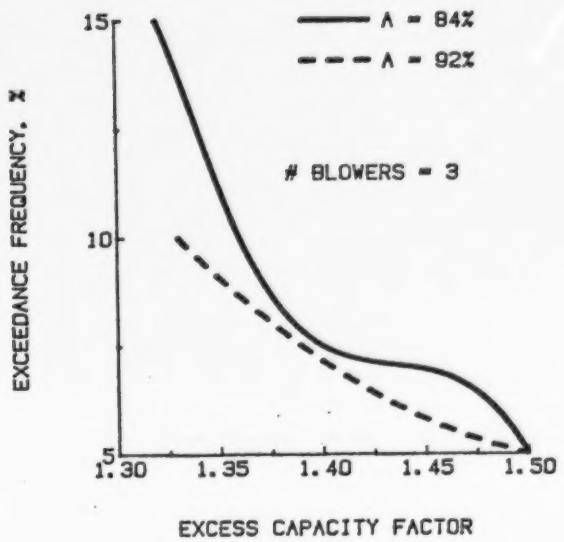

Figure 3. - Blower Sizing versus BOD Exceedance Frequency

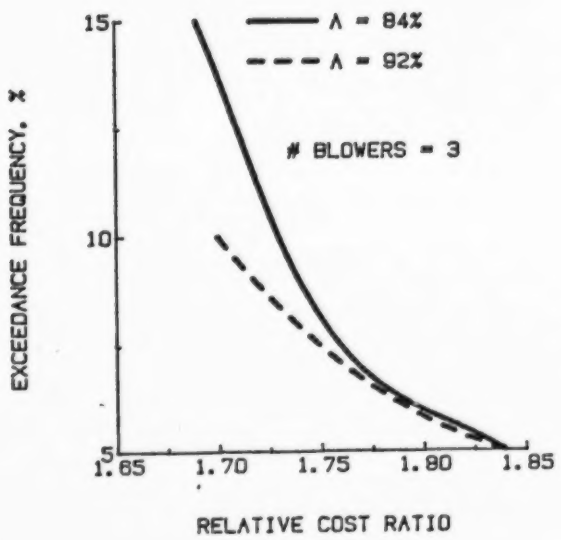

Figure 4. - Relative Blower Cost versus BOD Exceedance Frequency

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